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Exotic Higgs decays in the E_6 inspired SUSY models



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ABSTRACT

We study the decays of the SM-like Higgs state within the E_6 inspired supersymmetric (SUSY) models with exact custodial symmetry that forbids tree-level flavor-changing transitions and the most dangerous baryon and lepton number violating operators. In these models there are two states which are absolutely stable and can contribute to the dark matter density. One of them is the lightest SUSY particle (LSP) which is expected to be lighter than 1 eV forming hot dark matter in the Universe. The presence of another stable neutral state allows to account for the observed cold dark matter density. In the considered SUSY models next-to-lightest SUSY particle (NLSP) also tend to be light. We argue that the NLSP with GeV scale mass can result in the substantial branching ratio of the nonstandard decays of the lightest Higgs boson.

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1. Introduction

The observation of a new bosonic state with a mass around ~ 125 GeV [1,2] may provide a window into new physics beyond the Standard Model (SM). At the moment the observed signal strengths are consistent with the SM Higgs boson but more data is needed to assess the nature of the recently discovered state. Physics beyond the SM may affect the Higgs decay rates to SM particles and give rise to new channels of Higgs decays (for recent reviews of nonstandard Higgs boson decays see [3]). In particular, Higgs boson can decay with a substantial branching fraction into states which cannot be directly detected. Such invisible Higgs decay modes may occur in models with an enlarged symmetry breaking sector (Majoron models, SM with extra singlet scalar fields, etc.) [4,5], in “hidden valley” models [6], in the SM with a fourth generation of fermions [7], in the supersymmetric (SUSY) extensions of the SM [8],¹ in the models with compact and large extra dimensions [5,10], in the lightest Higgs model with T-parity [11], etc.

In the context of invisible Higgs decays it is especially interesting to consider the nature and extent of invisibility acquired by

the SM-like Higgs state within well motivated SUSY extensions of the SM. Here we focus on the E_6 inspired SUSY models which are based on the low-energy SM gauge group together with an extra $U(1)_N$ gauge symmetry defined by:

$$U(1)_N = \frac{1}{4}U(1)_\chi + \frac{\sqrt{15}}{4}U(1)_\psi. \quad (1)$$

The two anomaly-free $U(1)_\psi$ and $U(1)_\chi$ symmetries can originate from the breakings $E_6 \rightarrow SO(10) \times U(1)_\psi$, $SO(10) \rightarrow SU(5) \times U(1)_\chi$. To ensure anomaly cancellation the particle spectrum in these models is extended to fill out three complete 27-dimensional representations of the gauge group E_6 . Each 27-plet contains one generation of ordinary matter; singlet fields, S_i ; up and down type Higgs doublets, H_i^u and H_i^d ; charged $\pm 1/3$ coloured exotics D_i , \bar{D}_i . The presence of exotic matter in E_6 inspired SUSY models generically lead to non-diagonal flavour transitions and rapid proton decay. To suppress flavour changing processes as well as baryon and lepton number violating operators one can impose a set of discrete symmetries [12,13]. The E_6 inspired SUSY models with extra $U(1)_N$ gauge symmetry and suppressed flavor-changing transitions, as well as baryon number violating operators allow exotic matter to survive down to the TeV scale that may lead to spectacular new physics signals at the LHC which were analysed in [12–14]. Only in this Exceptional Supersymmetric Standard Model (E_6 SSM) [12,13] right-handed neutrinos do not participate in the gauge interactions so that they may be superheavy, shedding light on the origin of the mass hierarchy in the lepton sector and providing a mechanism for the generation of the baryon asymmetry in the Universe via leptogenesis [15]. Recently the particle spectrum and collider signatures associated with it were studied within the constrained version of the E_6 SSM [16].

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¹ Recently the nonstandard Higgs decays within the Next-to-Minimal Supersymmetric Standard model were discussed in [9].

In this Letter we consider the nonstandard Higgs decays within the E_6 inspired SUSY models in which a single discrete \tilde{Z}_2^H symmetry forbids tree-level flavor-changing transitions and the most dangerous baryon and lepton number violating operators [17]. These models contain at least two states which are absolutely stable and can contribute to the relic density of dark matter. One of these states is a lightest SUSY particle (LSP) while another one tends to be the lightest ordinary neutralino. The masses of the LSP and next-to-lightest SUSY particle (NLSP) are determined by the vacuum expectation values (VEVs) of the Higgs doublets. As a consequence they give rise to nonstandard Higgs boson decays. In the phenomenologically viable scenarios LSP should have mass around 1 eV or even smaller forming hot dark matter in the Universe while NLSP can be substantially heavier. NLSPs with GeV scale masses result in substantial branching ratios of the lightest Higgs decays into NLSPs. Since NLSP tend to be long-lived particle in this case it decays outside the detectors leading to the invisible decays of the SM-like Higgs state. In the considered E_6 inspired SUSY model the lightest ordinary neutralino can account for all or some of the observed cold dark matter relic density.

The Letter is organised as follows. In the next section we briefly review the E_6 inspired SUSY models with exact custodial \tilde{Z}_2^H symmetry. In Section 3 we specify a set of benchmark scenarios that lead to the invisible decays of the SM-like Higgs state mentioned above. Section 4 concludes the Letter.

2. E_6 inspired SUSY models with exact \tilde{Z}_2^H symmetry

In this section, we give a brief review of the E_6 inspired SUSY models with exact custodial \tilde{Z}_2^H symmetry [17]. These models imply that near some high energy scale (scale M_X) E_6 or its subgroup is broken down to $SU(3)_C \times SU(2)_W \times U(1)_Y \times U(1)_\psi \times U(1)_\chi \times Z_2^M$, where $Z_2^M = (-1)^{3(B-L)}$ is a matter parity. Below scale M_X the particle content of the considered models involves three copies of 27_i -plets and a set of M_i and \bar{M}_i supermultiplets from the incomplete $27'_i$ and $\bar{27}'_i$ representations of E_6 . All matter superfields, that fill in complete 27_i -plets, are odd under \tilde{Z}_2^H discrete symmetry while the supermultiplets \bar{M}_i can be either odd or even. All supermultiplets M_i are even under the \tilde{Z}_2^H symmetry and therefore can be used for the breakdown of gauge symmetry. In the simplest case the set of M_i includes H_u , H_d , S and L_4 , where L_4 and \bar{L}_4 are lepton $SU(2)_W$ doublet and anti-doublet supermultiplets that originate from a pair of additional $27'_i$ and $\bar{27}'_i$.

At low energies (i.e. TeV scale) the superfields H_u , H_d and S play the role of Higgs fields. The VEVs of these superfields ($\langle H_d \rangle = v_1/\sqrt{2}$, $\langle H_u \rangle = v_2/\sqrt{2}$ and $\langle S \rangle = s/\sqrt{2}$) break the $SU(2)_W \times U(1)_Y \times U(1)_N$ gauge symmetry down to $U(1)_{em}$ associated with the electromagnetism. In the simplest scenario \bar{H}_u , \bar{H}_d and \bar{S} are odd under the \tilde{Z}_2^H symmetry. As a consequence \bar{H}_u , \bar{H}_d and \bar{S} from the $\bar{27}'_i$ get combined with the superposition of the corresponding components from 27_i so that the resulting vector-like states gain masses of order of M_X . On the other hand L_4 and \bar{L}_4 are even under the \tilde{Z}_2^H symmetry. These supermultiplets form TeV scale vector-like states to render the lightest exotic quark unstable. In this simplest scenario the exotic quarks are leptoquarks.

The \tilde{Z}_2^H symmetry allows the Yukawa interactions in the superpotential that originate from $27'_i \times 27'_m \times 27'_n$ and $27'_i \times 27_i \times 27_k$. One can easily check that the corresponding set of operators does not contain any that lead to the rapid proton decay. Since the set of multiplets M_i contains only one pair of doublets H_d and H_u the \tilde{Z}_2^H symmetry also forbids unwanted FCNC processes at the tree level. The gauge group and field content of the E_6 inspired SUSY models considered here can originate from the orbifold GUT models in which the splitting of GUT multiplets can be naturally achieved [17].

Table 1

Transformation properties of different components of E_6 multiplets under \tilde{Z}_2^H , Z_2^M and Z_2^E discrete symmetries.

	27_i	27_i	$27'_{H_u}$ ($27'_{H_d}$)	$27'_S$	$\bar{27}'_{H_u}$ ($\bar{27}'_{H_d}$)	$\bar{27}'_S$	$27'_L$ ($27'_L$)
	$Q_i, u_i^c, d_i^c,$ L_i, e_i^c, N_i^c	$\bar{D}_i, D_i,$ H_i^d, H_i^u, S_i	H_u (H_d)	S	\bar{H}_u (\bar{H}_d)	\bar{S}	L_4 (\bar{L}_4)
\tilde{Z}_2^H	–	–	+	+	–	–	+
Z_2^M	–	+	+	+	+	+	–
Z_2^E	+	–	+	+	–	–	–

In the simplest scenario discussed above extra matter beyond the minimal supersymmetric standard model (MSSM) fill in complete $SU(5)$ representations. As a result the gauge coupling unification remains almost exact in the one-loop approximation. It was also shown that in the two-loop approximation the unification of the gauge couplings in the considered scenario can be achieved for any phenomenologically acceptable value of $\alpha_3(M_Z)$, consistent with the central measured low energy value [18].

As mentioned before, the gauge symmetry in the E_6 inspired SUSY models being considered here, is broken so that the low-energy effective Lagrangian of these models is invariant under both Z_2^M and \tilde{Z}_2^H symmetries. Since $\tilde{Z}_2^H = Z_2^M \times Z_2^E$ the Z_2^E symmetry associated with exotic states is also conserved. The transformation properties of different components of 27_i , $27'_i$ and $\bar{27}'_i$ supermultiplets under the \tilde{Z}_2^H , Z_2^M and Z_2^E symmetries are summarized in Table 1. The invariance of the Lagrangian under the Z_2^E symmetry implies that the lightest exotic state, which is odd under this symmetry, must be stable. Using the method proposed in [19] it was argued that there are theoretical upper bounds on the masses of the lightest and second lightest inert neutralino states [20].² These states are predominantly the fermion components of the two SM singlet superfields S_i from 27_i which are odd under the Z_2^E symmetry. Their masses do not exceed 60–65 GeV so that the lightest and second lightest inert neutralino states (\tilde{H}_1^0 and \tilde{H}_2^0) tend to be the lightest exotic particles in the spectrum [20].

The Z_2^M symmetry conservation ensures that R -parity is also conserved. Since the lightest inert neutralino \tilde{H}_1^0 is also the lightest R -parity odd state either the lightest R -parity even exotic state or the lightest R -parity odd state with $Z_2^E = +1$ must be absolutely stable. In the considered E_6 inspired SUSY models most commonly the second stable state is the lightest ordinary neutralino χ_1^0 ($Z_2^E = +1$). Both stable states are natural dark matter candidates.

When $|m_{\tilde{H}_1^0}| \ll M_Z$ the couplings of the lightest inert neutralino to the gauge bosons, Higgs states, quarks and leptons are very small resulting in very small annihilation cross section for $\tilde{H}_1^0 \tilde{H}_1^0 \rightarrow$ SM particles, making the cold dark matter density much larger than its measured value. In principle, \tilde{H}_1^0 could account for all or some of the observed cold dark matter density if it had a mass close to half the Z mass. In this case the lightest inert neutralino states annihilate mainly through an s -channel Z -boson [20,21]. However the usual SM-like Higgs boson decays more than 95% of the time into either \tilde{H}_1^0 or H_2^0 in these cases while the total branching ratio into SM particles is suppressed. Because of this the corresponding scenarios are basically ruled out nowadays [20].

The simplest phenomenologically viable scenarios imply that the lightest inert neutralinos are extremely light. For example,

² We use the terminology “Inert Higgs” to denote Higgs-like doublets and SM singlets that do not develop VEVs. The fermionic components of these supermultiplets form inert neutralino and chargino states.

these states can be substantially lighter than 1 eV.³ In this case, light \tilde{H}_1^0 forms hot dark matter in the Universe but gives only a very minor contribution to the dark matter density while the lightest ordinary neutralino may account for all or some of the observed cold dark matter density.

3. Nonstandard Higgs decays

As discussed earlier, the E_6 inspired SUSY models considered here involves three families of up and down type Higgs-like doublet supermultiplets (H_i^u and H_i^d) and three SM singlet superfields (S_i) that carry $U(1)_N$ charges. One family of the Higgs-like doublets and one SM singlet develop VEVs breaking gauge symmetry. The fermionic components of other Higgs-like and singlet superfields form inert neutralino and chargino states. The Yukawa interactions of inert Higgs superfields are described by the superpotential

$$W_{IH} = \lambda_{\alpha\beta} S(H_\alpha^d H_\beta^u) + f_{\alpha\beta} S_\alpha(H_d H_\beta^u) + \tilde{f}_{\alpha\beta} \tilde{S}_\alpha(H_\beta^d H_u), \quad (2)$$

where $\alpha, \beta = 1, 2$. Without loss of generality it is always possible to choose the basis so that $\lambda_{\alpha\beta} = \lambda_{\alpha\alpha} \delta_{\alpha\beta}$. In this basis the masses of inert charginos are given by

$$m_{\tilde{H}_\alpha^\pm} = \frac{\lambda_{\alpha\alpha}}{\sqrt{2}} s. \quad (3)$$

In our analysis here we shall choose the VEV of the SM singlet field s to be large enough ($s \simeq 12$ TeV) to ensure that the experimental constraints on Z' boson mass ($M_{Z'} \gtrsim 2$ TeV) and $Z - Z'$ mixing are satisfied. To avoid the LEP lower limit on the masses of inert charginos we also choose the Yukawa couplings $\lambda_{\alpha\alpha}$ so that all inert chargino states have masses which are larger than 100 GeV. In the following analysis we also require the validity of perturbation theory up to the GUT scale that constrains the allowed range of all Yukawa couplings.

Here we restrict our attention to the part of the parameter space that corresponds to $\lambda_{\alpha\alpha} s \gg f_{\alpha\beta} v, \tilde{f}_{\alpha\beta} v$. In that limit the inert neutralino states which are predominantly linear superpositions of the neutral components of inert Higgsinos, i.e. \tilde{H}_α^{d0} and \tilde{H}_α^{u0} , are normally heavier than 100 GeV and can be integrated out. Then the resulting 2×2 mass matrix can be written as follows

$$M_{IS} = -\frac{v^2 \sin 2\beta}{4m_{\tilde{H}_\alpha^\pm}} \begin{pmatrix} 2\tilde{f}_{11} f_{11} & \tilde{f}_{11} f_{21} + f_{11} \tilde{f}_{21} \\ \tilde{f}_{11} f_{21} + f_{11} \tilde{f}_{21} & 2\tilde{f}_{21} f_{21} \end{pmatrix} - \frac{v^2 \sin 2\beta}{4m_{\tilde{H}_\beta^\pm}} \begin{pmatrix} 2\tilde{f}_{12} f_{12} & \tilde{f}_{12} f_{22} + f_{12} \tilde{f}_{22} \\ \tilde{f}_{12} f_{22} + f_{12} \tilde{f}_{22} & 2\tilde{f}_{22} f_{22} \end{pmatrix}, \quad (4)$$

where $v = \sqrt{v_1^2 + v_2^2} \simeq 246$ GeV and $\tan \beta = v_2/v_1$. The mass matrix (4) can be easily diagonalized. Two lightest inert neutralino states \tilde{H}_1^0 and \tilde{H}_2^0 are predominantly inert singlinos. In our limit these states tend to be substantially lighter than 100 GeV.

When the SUSY breaking scale M_S is considerably larger than the electroweak (EW) scale, the mass matrix of the CP-even Higgs sector has a hierarchical structure and can be also diagonalized using the perturbation theory [23,24]. Here we are going to focus on the scenarios with moderate values of $\tan \beta$ ($\tan \beta < 2-3$). For these values of $\tan \beta$ the mass of the lightest CP-even Higgs boson m_{h_1} is very sensitive to the choice of the coupling $\lambda(M_t)$. In particular, in order to get $m_{h_1} \simeq 125$ GeV the coupling $\lambda(M_t)$

must be larger than $g'_1 \simeq 0.47$. When $\lambda \gtrsim g'_1$, the qualitative pattern of the Higgs spectrum is rather similar to the one which arises in the PQ symmetric NMSSM [25,24]. In the considered limit the heaviest CP-even, CP-odd and charged states are almost degenerate and lie beyond the TeV range while the mass of the second lightest CP-even Higgs state is set by $M_{Z'}$ [12]. In this case the lightest CP-even Higgs boson is the analogue of the SM Higgs field.

The lightest and second lightest inert neutralinos interact with the Z -boson and the SM-like Higgs state. The corresponding part of the Lagrangian, that describes these interactions, can be presented in the following form:

$$\mathcal{L}_{Zh} = \sum_{\alpha,\beta} \frac{M_Z}{2v} Z_\mu (\tilde{H}_\alpha^{0T} \gamma_\mu \gamma_5 \tilde{H}_\beta^0) R_{Z\alpha\beta} + \sum_{\alpha,\beta} (-1)^{\theta_\alpha + \theta_\beta} X_{\alpha\beta}^h (\psi_\alpha^{0T} (-i\gamma_5)^{\theta_\alpha + \theta_\beta} \psi_\beta^0) h, \quad (5)$$

where $\alpha, \beta = 1, 2$. In Eq. (5) $\psi_\alpha^0 = (-i\gamma_5)^{\theta_\alpha} \tilde{H}_\alpha^0$ is the set of inert neutralino eigenstates with positive eigenvalues, while θ_α equals 0 (1) if the eigenvalue corresponding to \tilde{H}_α^0 is positive (negative). The inert neutralinos are labeled according to increasing absolute value of mass, with \tilde{H}_1^0 being the lightest inert neutralino.

We further assume that the lightest inert neutralino is substantially lighter than 1 eV so that it gives only a very minor contribution to the dark matter density. On the other hand we allow the second lightest inert neutralino state to have mass in the GeV range. Although these states are substantially lighter than 100 GeV their couplings to the Z -boson can be rather small because of the inert singlino admixture in these states. Therefore any possible signal which these neutralinos could give rise to at former colliders would be extremely suppressed and such states could remain undetected.

The couplings of the Higgs states to the inert neutralinos originate from the superpotential (2). If all Higgs states except the lightest one are much heavier than the EW scale then the couplings of the SM-like Higgs boson to the lightest and second lightest inert neutralinos are determined by their masses [20]. Since we assumed that the mass of \tilde{H}_1^0 is lighter than 1 eV the couplings of the lightest Higgs boson to $\tilde{H}_1^0 \tilde{H}_1^0$ and $\tilde{H}_1^0 \tilde{H}_2^0$ are negligibly small and can be ignored in our analysis. Also because of this the experiments for the direct detection of dark matter do not set any stringent constraints on the masses and couplings of the lightest and second lightest inert neutralinos. In the considered case the coupling of the SM-like Higgs state to \tilde{H}_2^0 is basically proportional to the second lightest inert neutralino mass divided by the VEV, i.e. $X_{22}^h \simeq |m_{\tilde{H}_2^0}|/v$ [20]. This coupling gives rise to the decays of the lightest Higgs boson into \tilde{H}_2^0 pairs with partial widths given by

$$\Gamma(h_1 \rightarrow \tilde{H}_2^0 \tilde{H}_2^0) = \frac{(X_{22}^h)^2 m_{h_1}}{4\pi} \left(1 - 4 \frac{|m_{\tilde{H}_2^0}|^2}{m_{h_1}^2}\right)^{3/2}. \quad (6)$$

In order to compare the partial widths associated with the exotic decays of the SM-like Higgs state (6) with the Higgs decay rates into the SM particles we shall specify a set of benchmark points (see Table 2). For each benchmark scenario we calculate the spectrum of the inert neutralinos, inert charginos and Higgs bosons as well as their couplings and the branching ratios of the nonstandard decays of the lightest CP-even Higgs state. We fix $\tan \beta = 1.5$ and $\lambda(M_t) = 0.6$. As it was mentioned before, such a large value of $\lambda(M_t)$ allows m_{h_1} to be 125 GeV for moderate $\tan \beta$. In addition, we set stop scalar masses to be equal to $m_Q = m_U = M_S = 4$ TeV and restrict our consideration to the so-called maximal mixing scenario when the stop mixing parameter $X_t = A_t - \lambda s/(\sqrt{2} \tan \beta)$ is equal to $X_t = \sqrt{6} M_S$. From Table 2 it follows that the structure of

³ The presence of very light neutral fermions in the particle spectrum might have interesting implications for the neutrino physics (see, for example [22]).

Table 2

Benchmark scenarios for $m_{h_1} \approx 125$ GeV. The branching ratios and decay widths of the lightest Higgs boson, the masses of Inert neutralinos and charginos as well as the couplings of \tilde{H}_1^0 and \tilde{H}_2^0 are calculated for $s = 12000$ GeV, $\lambda = 0.6$, $\tan \beta = 1.5$, $m_{H^\pm} \simeq m_A \simeq m_{H_3} \simeq 9497$ GeV, $m_{h_2} \simeq M_{Z'} \simeq 4450$ GeV, $m_Q = m_U = M_S = 4000$ GeV and $X_t = \sqrt{6}M_S$.

	i	ii	iii	iv
λ_{22}	-0.03	-0.012	-0.06	0
λ_{21}	0	0	0	0.02
λ_{12}	0	0	0	0.02
λ_{11}	0.03	0.012	0.06	0
f_{22}	-0.1	-0.1	-0.1	0.6
f_{21}	-0.1	-0.1	-0.1	0.00245
f_{12}	0.00001	0.00001	0.00001	0.00245
f_{11}	0.1	0.1	0.1	0.00001
\tilde{f}_{22}	0.1	0.1	0.1	0.6
\tilde{f}_{21}	0.1	0.1	0.1	0.002
\tilde{f}_{12}	0.000011	0.000011	0.000011	0.002
\tilde{f}_{11}	0.1	0.1	0.1	0.00001
$ m_{\tilde{\chi}_1^0} /\text{GeV}$	$2.7 \cdot 10^{-11}$	$6.5 \cdot 10^{-11}$	$1.4 \cdot 10^{-11}$	$0.31 \cdot 10^{-9}$
$ m_{\tilde{\chi}_2^0} /\text{GeV}$	1.09	2.67	0.55	0.319
$ m_{\tilde{\chi}_3^0} /\text{GeV}$	254.6	101.8	509.1	169.7
$ m_{\tilde{\chi}_4^0} /\text{GeV}$	255.5	104.1	509.6	169.7
$ m_{\tilde{\chi}_5^0} /\text{GeV}$	255.8	104.9	509.7	199.1
$ m_{\tilde{\chi}_6^0} /\text{GeV}$	256.0	105.2	509.8	199.4
$ m_{\tilde{\chi}_1^\pm} /\text{GeV}$	254.6	101.8	509.1	169.7
$ m_{\tilde{\chi}_2^\pm} /\text{GeV}$	254.6	101.8	509.1	169.7
$ R_{Z11} $	0.0036	0.0212	0.00090	$1.5 \cdot 10^{-7}$
$ R_{Z12} $	0.0046	0.0271	0.00116	$1.7 \cdot 10^{-4}$
$ R_{Z22} $	0.0018	0.0103	0.00045	0.106
$X_{22}^{h_1}$	0.0044	0.0106	0.0022	0.00094
$\text{Br}(h \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_2^0)$	4.7%	21.9%	1.23%	0.22%
$\text{Br}(h \rightarrow b\bar{b})$	56.6%	46.4%	58.7%	59.3%
$\Gamma(h \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_2^0)/\text{MeV}$	0.194	1.106	0.049	0.0088
$\Gamma^{\text{tot}}/\text{MeV}$	4.15	5.059	4.002	3.962

the Higgs spectrum is extremely hierarchical. In Table 2 the masses of the heavy Higgs states are computed in the leading one-loop approximation. In the case of the lightest Higgs boson mass the leading two-loop corrections are taken into account.

Since the structure of the Higgs spectrum is very hierarchical, the partial decay widths that correspond to the decays of the lightest CP-even Higgs state into the SM particles are basically the same as in the SM. Because of this, for the calculation of the Higgs decay rates into the SM particles we use the results presented in [26] where these rates were computed within the SM for different values of the Higgs mass. When $m_{h_1} \simeq 125$ GeV the SM-like Higgs state decays predominantly into b -quark. In the SM the corresponding branching ratio is about 60% whereas the branching ratios associated with Higgs decays into WW , ZZ and $\gamma\gamma$ are about 20%, 2.1% and 0.23% respectively [26]. The total decay width of the Higgs boson near 125 GeV is 3.95 MeV.

For the calculation of the Higgs decay rates into $\tilde{H}_2^0 \tilde{H}_2^0$ we use Eq. (6). From this equation one can see that the branching ratios of the SM-like Higgs state into the second lightest inert neutralinos depend rather strongly on the masses of these exotic particles. When \tilde{H}_2^0 is relatively heavy, i.e. $m_{\tilde{H}_2^0} \gg m_b(m_{h_1})$, the lightest Higgs boson decays predominantly into $\tilde{H}_2^0 \tilde{H}_2^0$ while the branching ratios for decays into SM particles are suppressed. To ensure that the observed signal associated with the Higgs decays into $\gamma\gamma$ is not too much suppressed we restrict our consideration here to the GeV scale masses of the second lightest inert neutralino.

The set of the benchmark points (i)–(iv) that we specify in Table 2 demonstrates that one can get extremely light \tilde{H}_1^0 with mass

~ 0.1 – 0.01 eV, relatively light \tilde{H}_2^0 , that has a mass of the order of 1–0.1 GeV, and a relatively small value of the coupling R_{Z12} that allows the second lightest inert neutralino to decay within a reasonable time. In these benchmark scenarios the second lightest inert neutralino decays into the lightest one and a fermion–antifermion pair via virtual Z . Since R_{Z12} is relatively small \tilde{H}_2^0 tend to have a long lifetime. If the second lightest inert neutralino state decays during or after Big Bang Nucleosynthesis (BBN) it may destroy the agreement between the predicted and observed light element abundances. To preserve the success of the BBN, \tilde{H}_2^0 should decay before BBN, i.e. its lifetime $\tau_{\tilde{H}_2^0}$ has to be smaller than something like 1 s. This requirement constrains $|R_{Z12}|$. Indeed, for $m_{\tilde{H}_2^0} = 1$ GeV the absolute value of the coupling R_{Z12} should be larger than $1 \cdot 10^{-6}$ [27]. On the other hand the value of $|R_{Z12}|$ becomes smaller when the mass of the lightest inert neutralino decreases. Therefore in general sufficiently large fine tuning is needed to ensure that $|R_{Z12}| \gtrsim 10^{-6}$ for sub-eV lightest inert neutralino state. The constraint on $|R_{Z12}|$ becomes much more stringent with decreasing $m_{\tilde{H}_2^0}$ because $\tau_{\tilde{H}_2^0} \sim 1/(|R_{Z12}|^2 m_{\tilde{H}_2^0}^5)$. As a result, it is somewhat problematic to satisfy this restriction for $m_{\tilde{H}_2^0} \lesssim 100$ MeV.

The benchmark scenarios (i)–(iv) presented in Table 2 indicate that the branching ratio of the decays of SM-like Higgs boson into second lightest inert neutralino can vary from 0.2% to 20% (i.e. from 0% to 20% for practical purposes) when $m_{\tilde{H}_2^0}$ changes from 0.3 GeV to 2.7 GeV. For smaller (larger) values of the second lightest inert neutralino masses, the branching ratio associated with these nonstandard decays of the lightest CP-even Higgs states is even smaller (larger). At the same time the couplings of \tilde{H}_1^0 and \tilde{H}_2^0 to the Z -boson are so tiny that the lightest and second lightest inert neutralino states could not be observed before. In particular, their contribution to the Z -boson width tend to be rather small. The Z -boson invisible width is characterized by the effective number of neutrino species N_ν^{eff} . Its measured value is $N_\nu^{\text{exp}} = 2.984 \pm 0.008$ [28] whereas in the SM $N_\nu^{\text{eff}} = 3$. The contributions of the lightest and second lightest inert neutralino states to the Z -boson width can be parameterized similarly. In the case of benchmark scenarios (i), (ii), (iii), (iv) the effective numbers of neutrino species associated with these contributions are $5.8 \cdot 10^{-5}$, 0.002, $3.7 \cdot 10^{-6}$ and 0.011 respectively.

The second lightest inert neutralino states, that originate from the decays of the SM-like Higgs boson, sequentially decay into \tilde{H}_1^0 and pairs of leptons and quarks via virtual Z . Thus, in principle, the exotic decays of the lightest CP-even Higgs state results in two fermion–antifermion pairs and missing energy in the final state. Nevertheless because coupling R_{Z12} is quite small \tilde{H}_2^0 tend to live longer than 10^{-8} s. As a consequence the second lightest inert neutralino state typically decays outside the detectors and will not be observed at the LHC. Therefore the decay channel $h_1 \rightarrow \tilde{H}_2^0 \tilde{H}_2^0$ normally give rise to an invisible branching ratio of the SM-like Higgs boson. Such invisible decays of the lightest CP-even Higgs state take place in the benchmark scenarios (i), (iii) and (iv). In the case of benchmark scenario (ii) the absolute value of R_{Z12} coupling is larger than in other benchmark scenarios so that $\tau_{\tilde{H}_2^0} \sim 10^{-11}$ s.

In this case some of the decay products of \tilde{H}_2^0 produced through the decays $h_1 \rightarrow \tilde{H}_2^0 \tilde{H}_2^0$ might be observed at the LHC. In particular, we hope that it might be possible to detect the relatively energetic $\mu^+ \mu^-$ pairs that come from these exotic decays of the lightest CP-even Higgs state.

4. Conclusions

In this Letter we have considered the nonstandard decays of the lightest Higgs boson within well motivated SUSY extensions of the SM based on the $SU(3)_C \times SU(2)_W \times U(1)_Y \times U(1)_N \times Z_2^M$ symmetry. The low energy matter content of these E_6 inspired models includes three 27 representations of E_6 and a pair of $SU(2)_W$ doublets L_4 and \bar{L}_4 . In particular, the low-energy spectrum of the SUSY models being considered here involves three families of Higgs-like doublets H_i^d and H_i^u , three families of exotic quarks D_i and \bar{D}_i as well as three SM singlets S_i that carry $U(1)_N$ charges. In order to suppress flavour changing processes at the tree-level and forbid the most dangerous baryon and lepton number violating operators we imposed \tilde{Z}_2^H discrete symmetry under which one pair of Higgs-like doublet supermultiplets, one SM-type singlet superfield, L_4 and \bar{L}_4 are even while all other superfields are odd. The pair of the Higgs-like doublets and SM singlet, which are even under \tilde{Z}_2^H symmetry, acquire VEVs forming a Higgs sector. The fermionic components of the Higgs-like and SM singlet superfields, which are \tilde{Z}_2^H odd, compose a set of inert neutralino and chargino states. The lightest and second lightest inert neutralino (\tilde{H}_1^0 and \tilde{H}_2^0) which are predominantly inert singlinos tend to be LSP and NLSP in these E_6 inspired SUSY models. In the simplest phenomenologically viable scenarios LSP is expected to be substantially lighter than 1 eV and form hot dark matter in the Universe. Since LSP is so light it gives only minor contribution to the dark matter density. Because of the conservation of the Z_2^M and \tilde{Z}_2^H symmetries the lightest ordinary neutralino can be also absolutely stable and may account for all or some of the observed cold dark matter density.

The presence of light LSP and NLSP in the particle spectrum gives rise to new decay channels of the Z -boson and the SM-like Higgs state. In order to illustrate this, we specified a set of the benchmark points. The results of our analysis indicate that the couplings of \tilde{H}_1^0 and \tilde{H}_2^0 to the Z -boson can be very small so that these states could escape detection at former and present experiments. The couplings of the SM-like Higgs boson to the LSP and NLSP are determined by their masses. Since \tilde{H}_1^0 is expected to be extremely light it does not affect Higgs phenomenology. At the same time we argued that the NLSP with the GeV scale masses gives rise to the substantial branching ratio of the nonstandard decays of the lightest Higgs boson, i.e. $h_1 \rightarrow \tilde{H}_1^0 \tilde{H}_2^0$. After being produced the second lightest inert neutralino states sequentially decay into the LSP and pairs of leptons and quarks via virtual Z . Thus these decays of the lightest CP-even Higgs state lead to two fermion–antifermion pairs and missing energy in the final state. However due to the small couplings of the NLSP to the Z -boson the second lightest inert neutralino states tend to decay outside the detectors resulting in the invisible branching ratio of the lightest CP-even Higgs boson.

The branching fraction of the nonstandard Higgs decays depend rather strongly on the mass of the NLSP. When $m_{\tilde{H}_2^0} \gg m_b(m_{h_1})$ the lightest Higgs boson decays mainly into $\tilde{H}_1^0 \tilde{H}_2^0$ leading to the suppression of the branching ratios for the decays of h_1 into SM particles. To avoid such suppression we restrict our consideration to the GeV scale masses of \tilde{H}_2^0 . On the other hand we also required that the second lightest inert neutralino states decay before BBN, i.e. their lifetime is shorter than 1 s. This requirement rules out too light \tilde{H}_2^0 because $\tau_{\tilde{H}_2^0} \sim 1/(m_{\tilde{H}_2^0}^5)$. Our numerical analysis indicates that it is rather problematic to satisfy this restriction for $m_{\tilde{H}_2^0} \lesssim 100$ MeV. The set of the benchmark points that we specified demonstrates that the branching ratio of the non-standard decays of the lightest Higgs state can be as large as 20–30% if the second lightest inert neutralino is heavier than 2.5 GeV. When this inert

neutralino state is lighter than 0.5 GeV the corresponding branching ratio is suppressed so that it can be as small as 10^{-3} – 10^{-4} .

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